The 19th International Modal Analysis Conference, Orlando, FL, USA, February 5-8, 2001.

MODEL VALIDATION FOR A COMPLEX JOINTED STRUCTURE

Thomas A. Butler,[1] François M. Hemez,[2] John Schultze,[3] Hoon Sohn,[4] Scott W. Doebling[5]
Los Alamos National Laboratory
Engineering Sciences & Applications Division
Engineering Analysis Group (ESA-EA)
P.O. Box 1663, M/S P946, Los Alamos, New Mexico 87545

ABSTRACT

An overview of the modeling and validation of a complex engineering simulation performed at the Los Alamos National Laboratory is presented. The application discussed represents the highly transient response of an assembly with complex joints subjected to an impulsive load. The primary sources of nonlinearity were the contact mechanics. Several tests were conducted to assess the degree of experimental uncertainty, the variability of the geometry of the test article and its assembly procedures, and to provide reference data for model validation. After presenting the experiment and the corresponding numerical simulation, several issues of model validation are addressed. They include data reduction, feature extraction, design of computer experiments, statistical effects analysis, and model updating. It is shown how these tools can help the analyst gain confidence regarding the predictive quality of the simulation.

1 INTRODUCTION

Quantifying shock transmission through complex, jointed structures has traditionally been possible only with experimental methods. These experiments are expensive and time-consuming and thus only a few cases can be studied. With the advent of large scale computing capabilities estimation of the shock transmission with numerical models has become a tractable problem. A primary advantage of these models is that, when validated, parametric studies can be efficiently performed to evaluate the effects of different input loads and variations to the structure's design or to load path changes caused by aging. The U.S. Department of Energy's Accelerated Strategic Computing Initiative (ASCI) is developing massively parallel hardware and software environments for modeling these types of problems.

The ASCI computing environment is being used at Los Alamos to study the transmission of shock through a complex, jointed structure that is similar to structures used in both conventional and non-conventional, defense applications. A three-dimensional explicit model has been developed that includes a detailed representation of the geometry and contact surfaces including preloading effects. A series of full-scale experiments has been performed to provide data for model updating and validation.

After describing the experiments, the data collected, and the finite element model, several issues of open research are addressed. First, large computer simulations tend to generate enormous amounts of output that must be synthesized into a small number of indicators for the analysis. This step is referred to as data reduction or feature extraction [1]. These features are typically used to define the test-analysis correlation metrics optimized to improve the predictive accuracy of the model. The main issue in feature extraction is to define indicators that provide meaningful insight regarding the ability of the model to capture the dynamics investigated. The features used for analyzing this nonlinear, transient data sets are presented.

Second, efficient numerical optimization requires that the correlation between the model's input variables and output features be assessed with adequate accuracy. Statistical meta-models must be generated to replace the expensive, large-scale simulations. One difficulty of fitting meta-models is efficient sampling, that is, the generation of sufficient information in regions where the feature's joint probability

[1] Technical Staff Member, butler@lanl.gov, 505-667-6578 (Phone), 505-665-2137 (Fax).
[2] Technical Staff Member, hemez@lanl.gov, 505-665-7955 (Phone), 505-665-2137 (Fax).
[3] Postdoctoral Research Associate, schultze@lanl.gov, 505-667-9081 (Phone), 505-665-2137 (Fax).
[4] Postdoctoral Research Associate, sohn@lanl.gov, 505-667-6135 (Phone), 505-665-2137 (Fax).
[5] Technical Staff Member, doebling@lal.gov 505-667-6950 (Phone), 505-665-2137 (Fax).

density function is maximum. The sampling method for updating the numerical model is described and then results of applying the sampling technique and selected features to the determination of main effects are presented.

2 HARDWARE DESCRIPTION

The test article used for the experiments and subsequent analyses consists of several components fabricated from a variety of materials. A titanium component designated the "mount" to which all other components are attached is shown in Figure 1. Referring to this figure together with the finite element mesh shown in Figure 4 in section 4 while describing the assembly of the test article makes the configuration more understandable. The upper payload mass simulator, which is fabricated from 6061-T6 aluminum is bolted to the three feet on the upper end of the mount. The lower payload mass simulator, which is fabricated from carbon steel is held inside the mount using a tapered tape joint. The tapered tape is fabricated from SS304 stainless steel and is inserted through the thin, horizontal slot near the base of the mount. Separate pieces of the tapered tape are driven in, wedging the mass simulator against an inner retaining surface.

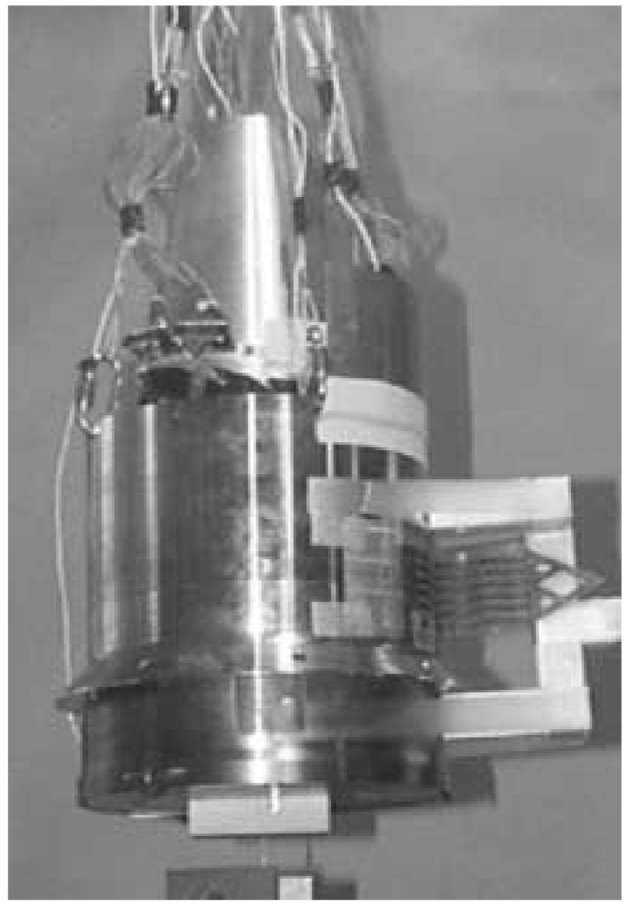
Figure 1: Titanium mount that connects all components of test article.

The lower shell, fabricated from 7075-T4 aluminum and then anodized, is placed over the titanium and its rim sits on a ledge just below the threaded portion of the mount. Next a titanium retaining nut threads onto the titanium mount bearing against the upper surface of the lower shell rim. It is torqued to a specified value. Finally, the upper shell, also fabricated from 7075-T4 aluminum, is threaded onto the mount. As it is torqued to a specified value, the load between the retaining nut and lower shell is reduced.

3 VALIDATION EXPERIMENTS

To date four experiments have been performed on the test article. These tests were performed by SRI International at their Menlo Park, California facility. For the experiments the test article was suspended using wire rope creating a pendulum with a length of about 1 m (Figure 2). Pendulum motion was monitored to determine the total impulse delivered to the test article.

Figure 2: The test article is shown in the test configuration with the explosive source attached.



For each experiment new upper and lower aluminum shells were used to ensure that accumulated damage did not affect test results. For three of these tests the shells were manufactured with “loose” tolerances. In other words, the shells were fabricated as nearly as possible to the upper end of the tolerance specification. For the forth test the shells were fabricated with “tight” tolerances. During assembly of the test article for the first, second, and fourth tests the lower shell was forced to be tight against the mount on the loaded side of the test article. For the third test the lower shell was forced to be tight against the mount on the side opposite the load. That is, it had the maximum possible gap between the shell and mount directly behind the explosive source. The resulting test matrix is shown in Table 1.

TABLE 1: Test matrix for explosively driven shock tests.

	Loose assembly	Tight assembly
Loose Tolerance	Test no. 3	Test nos. 1 , 2
Tight Tolerance		Test no. 4

3.1 Explosive Source

An explosive source was developed and characterized to apply an impulsive load to a portion of the outside surface of the test article. The source was fabricated from strips of thin explosive sheet material. Each strip was 0.48 mm thick and 1.27 mm wide. Spacing between strips was 6.86 mm. The pressure at the surface of the test article was moderated with a buffer material made from 3.18-mm-thick solid neoprene. The explosive strips were simultaneously initiated using an explosive lens. Characterization of the source involved using thick plates of aluminum target material containing plugs that could fly free. Measuring the velocity of these plugs and measuring the pressure with miniature piezoresistive sensors ensured that the desired impulse was realized. Additional verification of the impulse was obtained by measuring the change in velocity of the test article for each test. Figure 3 shows the pressure time histories of the pressure acting on the test article both directly under an explosive strip and half way between two strips.

The final geometry of the explosive source was 38-mm-high by 102-mm-long (circumferential direction). It was placed such that 12.7 mm was below the intersection between the upper and lower shells and 25.4 mm was above the intersection. The portion on the upper shell was directly outside the threaded intersection between the shell and the titanium mount.

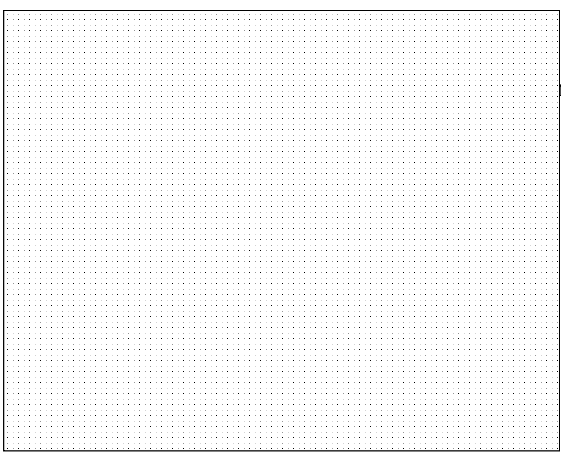


Figure 3: Pressure measured on aluminum substrate surface under neoprene buffer.

3.2 Instrumentation

The test article was instrumented with 33 strain gages and 6 accelerometers. The strain gages were attached to the inside surface of the titanium mount and had an active length of 0.8 mm to obtain localized effects. The six accelerometers were Endevco Model 7270A-200k and were located on either end of both payload mass simulators. Four were oriented laterally in the direction of the delivered impulse and two were oriented along the axis of the structure. The accelerometer signals had a frequency response of 500 kHz and the conditioned strain signals had a frequency response of 100 kHz.

3.3 Experimental Results

Measured strains ranged up to approximately 0.01 and peak accelerations after low-pass filtering at 50 kHz ranged up to about 10 000 g. Changes in rigid body velocity for the tests validated the total impulse measured during the characterization experiments. Test results are discussed further in following sections

4 NUMERICAL MODEL

The explicit finite element model (FEM) of the test article was developed using the ParaDyn finite element code [2]. The resulting model had approximately 1.4 million 8-node hexahedral elements, 56 000 4-node shell elements, and 1.8 million node points. Contact among the various test article components was modeled with 480 contact pairs. This large number of pairs was required because each individual surface, usually circumferential in nature, had to be broken in to several individual surfaces to accommodate efficient partitioning for the parallel code. Automatic contact capabilities that are currently under development in ParaDyn will obviate the need to break the contact into so many surfaces. Figure 4 shows a cross-section of the finite element model that illustrates the mesh density at most of the contact interfaces.

All material models were elastic since the loads for the first four experiments were low enough to keep all components in the elastic range. The only source of nonlinearity was, therefore, motion at the contact surfaces. The nonlinearity at these interfaces can be quite severe as shown in Figures 5 and 6 where the predicted contact forces across two interfaces are shown. The first case shown is a segment of a thread between the upper shell and mount directly under the explosive charge. Note that when the force is zero the threads have separated. The second case shown is the vertical interface between the upper shell and mount directly above the threaded region. Here the opening and closing of the gap is obvious.

Because the contact involved interfaces among stainless steel, carbon steel, anodized 7075-T4 aluminum, 6061-T6 aluminum, and titanium, precise selection of static and kinetic coefficients of friction was not possible. Some of the variables that contribute to the coefficient of friction include surface finish and hardness and the presence of lubricants. Since these were not known, these coefficients of friction were estimated by bounds and allowed to vary between specified limits among different runs as described in later sections.

Preloading due to assembly of the threaded joints and the tape joint was accomplished in the model by implementing an orthotropic thermal coefficient of expansion in specific layers of elements. At the start of each analysis the temperature was increased using a half-cosine time history over 0.2 ms. The structure was then allowed to freely respond with no additional input for 0.1 ms before the explosive impulse was applied. Lacking a precise definition of the coefficient of friction also led to unknown levels of these preloads. Therefore, the preloads were also allowed to vary between specified limits among the different runs.

The impulse from the explosive source was applied over the appropriate region of the test article as a pressure time history. Since the explosive strips were center-detonated, the pressure pulse arrived at each circumferential position at a different point in time. This time delay was accommodated in the model by dividing the loaded region into vertical strips of elements and using the appropriate time of arrival for each element strip.

The finite element model was run on 504 processors on the Los Alamos Blue Mountain computer. Using this number of processors resulted in 1.3 cpu hours for each ms of the simulation.

5 UPDATING AND VALIDATION FEATURES

The first aspect in determining which features are appropriate for model updating and model validation is consideration of what the model will be used to predict. For instance, if the model will be used to predict only peak acceleration at a given point it is not necessary to consider the time of arrival of the peak or the frequency content of the acceleration data. In this case the feature is a single number representing the peak acceleration. If the designer or analyst is concerned not only with the peak level of acceleration, but also the frequency content of the acceleration history, the shock response spectrum (SRS) may be an appropriate measure of the system's response. However, in general, the SRS is ambiguous in that an infinite number of transients can lead to the same SRS. An alternative measure of frequency content is the Fourier transform of the acceleration history. Here the analyst has the freedom to choose the frequency range of interest and compare the transform only in those frequency bands. Other features of response that might make sense could include counting the number of times that a strain history exceeds certain levels. This feature may be appropriate for certain fatigue analyses.

A second aspect in determining the appropriate features is to select features that have a dimensionality low enough to make comparison tractable. Comparing two acceleration histories point by point is not a good choice. A choice such as this becomes even more impossible if the accelerations at several different points need to be compared. An obvious alternative of simply using the root mean square (RMS) level of acceleration, however, may not give sufficient information. Other options for reducing dimensionality that are frequently used are comparing mode shapes and frequencies or measures of their differences. This option is strictly applicable only to linear systems.

In the case of the test article being considered here the desire is to fully characterize the acceleration and strain responses at specific locations over a wide frequency range (0.5 – 30 kHz). As an alternative, the use of principal component analysis is being investigated. Time histories from 6 accelerometers or 33 strain gages are condensed to a single time history by projecting onto the first principal component.

To further reduce the dimensionality of the data, an auto-regressive moving average (ARMA) model is fit to the time series projected onto the first principal component derived from the covariance matrix of numerical data. Then, this ARMA model is used to reproduce the response of the actual experimental system, and the prediction errors are computed.

This approach is based on the premise that if the ARMA model estimated from the FE model is a good representation of the actual system, the dynamic characteristics of the numerical model should be similar to those of the actual system based on some measure of "similarity". That is, if the numerical model is close enough to the actual system, the ARMA prediction model should be able to reproduce the experimental data reasonable well resulting in small prediction errors. Therefore, the variance of these prediction errors are defined as the primary feature for the model updating presented here.

The ARMA based feature does not give a measure of the RMS response so, in addition to this feature, the RMS value of a vector representing the differences values of individual acceleration or strain histories from the test and FEM predictions is used. An additional feature being considered but not yet implemented include a measure of the energy content distribution in the frequency domain of the time history.

6 SAMPLING METHODS

Efficient model updating and validation requires that the correlation between the model's input variables and output features be assessed with good accuracy. Statistical meta-models must be generated to replace the expensive, large-scale simulations. One difficulty of fitting meta-models is efficient sampling, that is, the generation of sufficient information in regions where the feature's joint probability density function is at its maximum. The approach used here was to first use a sparse sampling to determine what the main effects are and then to down select on the number of input parameters considered. A denser sampling is then performed over the reduced set of parameters.

The design-of-experiments method [4] was used to select the computer simulations that would be most efficient for determining which parameters were the main effects. This set of simulations is called the design matrix. In establishing the design matrix care must be taken to use enough simulations to avoid aliasing that may bias the subsequent statistical analysis. Aliasing in statistical modeling is caused by using sampling of the input space that is too sparse. The result can be contamination of main effects by secondary effects.

If the design matrix is based on orthogonal variable arrays the columns of the input space are linearly independent. This independence results in the ability to distinguish the variance associated with the linear aspect (main effect) of a variable from the other variables. It does not imply that it is not confounded or aliased with second order or higher effects. However, if the design matrix is based on the Taguchi method the columns are not correlated with other columns and, in addition, they are free of interaction with second-order effects. This makes for efficient linear screening with a limited set of simulations.

After the design matrix is established, the finite element package is run at the corresponding combinations of input parameters and results are gathered for feature extraction. Then, statistical tests are implemented to assess the global contribution of each input parameter to the total variability observed from the computer simulations. A popular example is the R-square (R^2) statistics that estimates Pierson's correlation ratio. It is defined as the ratio between the variance that can be attributed to a given effect and the total variance of the data [5].

7 RESULTS

As described in the previous section, the first step in the development of a parameter set to be used for model updating and response surface construction is the screening of the main effects of the candidate variables. This assesses the amount of variation of the model that can be explained by the different variables. Ideally the variables that have significant effect on the model will also have significant contribution to the variance of the selected feature. As described in section 5, the primary feature that has been applied to date is the comparison of the simulation's prediction to an ARMA model fit to the experimental data.

The design matrix for extracting main effects was developed based on 11 variables (input parameters) varied over 32 simulations. Table 2 lists the input parameters that were varied during the analyses. Figure 7 shows the results of the analysis. The first graph in the figure shows the analyst's expected results based on engineering judgement and a thorough knowledge of the test article. The second graph shows the results based on the ARMA modeling technique. It is clear from the figure that variables 2, 3, 6, 7, 10 are significant. The symbols σ_{22} and σ_{21} are the variances of the prediction errors of the FEM and experimental responses, respectively, estimated by the ARMA model that was based on the FEM results.

TABLE 2: Parameters for main effects analysis

	Description
1	tapered tape preload
2	retaining nut preload
3	upper shell preload
4	Aluminum/aluminum static friction coefficient
5	Steel/steel static friction coefficient
6	Aluminum/titanium static friction coefficient
7	Steel/titanium static friction coefficient
8	Aluminum/aluminum kinetic friction coefficient
9	Steel/steel kinetic friction coefficient
10	Aluminum/titanium static friction coefficient
11	Steel/titanium static friction coefficient

Also from the figure, it is clear that the statistical analysis performed on the feature yields results that match well with analyst predictions. This partially confirms that the feature is extracting information that is useful. A current effort will lead to selection of a second, independent, feature that will be used to confirm that the indicated variables indeed are the main effects and should be used for the more detailed analysis that will rigorously define the statistical meta-model. For further details regarding the methodology followed for design of computer experiments, statistical model fits, and model updating, the reader is referred to a companion paper [6].

Figure 7: Results of preliminary main effects analysis using ARMA-based features and a Taguchi design matrix

8 CONCLUSIONS

Even though the results are preliminary at this point, analyses to date have shown that a very large FEM can be efficiently validated and updated if modern statistical methods are applied. In addition, early indications are that a large model that has to simulate significant nonlinearities can simulate response to a highly impulsive load throughout the frequency range of interest.

Further work is needed to develop additional features for use in both model updating and validation. Also, additional experiments are required since the four available at this time are probably not different enough to fully validate the model over the load ranges of interest.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the work performed by SRI International under the leadership of Mark Groethe to complete the set of experiments on the test article. We also acknowledge the support of the weapons program at Los Alamos for supplying the resources needed to accomplish the test program and the support of the Department of Energy Accelerated Strategic Computing

Initiative Program Office and the ASCI Project at Los Alamos. The Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under Contract W-7405-ENG-36.

REFERENCES

[1] Bishop,C.M., **Neural Networks for Pattern Recognition**, Clarendon Press, Oxford University Press, Inc., New York, NY, 1998.

[2] Hoover, C. G., De Groot, A. J., Sherwood, R. J., "ParaDyn: A Parallel Nonlinear, Explicit, Three-Dimensional Finite-Element Code for Solid and Structrual Mechanics--User Manual," Lawernce Livermore National Laboratory, Livermore, California, UCRL-MA, 2000, to appear.

[3] Sohn, H., Farrar, C., "Time Series Analyses For Locating Damage Sources in Vibration Systems," *25th International Conference on Noise and Vibration Engineering (ISMA)*, Leuven, Belgium, Sept. 13-15, 2000, pp. 187-191.

[4] Hedayat, A.S., Sloane, N.J.A., Stufken, J., Orthogonal Arrays: Theory and Applications, Springer-Verlag, New York, NY, 1999.

[5] McKay, M.D., Beckman, R.J., Conover, W.J., "A Comparison of Three Methods for Selecting Values of Input Variables iin the Analysis of Output From a Computer Code", Technometrics, Vol. 21, No. 2, 1979, pp. 239-245.

[6] Schultze, J.F., Hemez, F.M., Doebling, S.W., Hoon, S., "Statistical Based Non-linear Model Updating Using Feature Extraction," *19th International Modal Analysis Conference (IMAC),* Kissimmee, FL, Feb. 5-8, 2001, to appear.